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Sustainable options for electric vehicle technologies

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ABSTRACT

In this work, an overview regarding electric vehicle technologies and associated charging mechanisms is carried out. The review covers a broad range of topics related to electric vehicles, such as the basic types of these vehicles and their technical characteristics, fuel economy and CO_2 emissions, the electric vehicle charging mechanisms and the notions of grid to vehicle and vehicle to grid architectures. In particular three main types of electric vehicles, namely, the hybrid electric vehicles (HEVs), the plug-in electric vehicles (PHEVs) and the full electric vehicles (FEVs) are discussed in detailed. The major difference between these types of vehicles is that for the last two types, the battery can be externally recharged. In addition, FEVs operate only on battery charge and therefore always employ the charge depleting mode of operation requiring high power, high energy battery packs. On the other hand, PHEVs offer the possibility of on-board battery charging and the option of charge depleting or charge sustaining modes of operation. Finally HEVs, which were the first type of electric vehicles to be manufactured, offer higher travelling range compared to PHEVs and FEVs due to the existence of the internal combustion engine. Although tank-to-wheel efficiencies of electric vehicles show that they have higher fuel economies than conventional gasoline vehicles, the well-to-wheel efficiency is a more appropriate measure to use for comparing fuel economy and CO_2 emissions in order to account for the effect of electricity consumption from these vehicles. From the perspective of a full cycle analysis, the electricity available to recharge the batteries must be generated from renewable or clean sources in order for such vehicles to have zero emissions. On the other hand, when electric vehicles are recharged from electricity produced from conventional technology power plants such as oil or coal-fired plants, they may produce equal or sometimes more greenhouse gas emissions than conventional gasoline vehicles.

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1. Introduction

Growing concerns over climate change and security of energy supply are driving a shift in the transport sector from fossil to alternative fuels and new electric vehicle propulsion systems capable of delivering long-term sustainability. Globally three quarters of transport greenhouse emissions come from road transport. The transport sector is especially vulnerable to oil supply disruption and price volatility and despite huge reductions in emissions of harmful emissions, concerns over air quality and noise, especially in urban areas are also under consideration [1].

Electric vehicles are a promising technology for the drastic reduction of road transport emissions. This is an important element in reducing carbon dioxide (CO_2) emissions, air pollutants and noise from passenger cars and light commercial vehicles. At the same time, the electric passenger cars that are under development are not yet competitive with conventional vehicle technology [2]. Costs are still high and battery technology is still under developed leading to many uncertainties with respect to crucial issues, such as battery technology, impacts on emissions, interaction with electricity generation and costs and business case of large-scale introduction.

In this work, an overview regarding electric vehicle technologies and associated charging mechanisms is carried out. The review covers a broad range of topics related to electric vehicles, such as the basic types of these vehicles and their technical characteristics, fuel economy and CO_2 emissions, the electric vehicle charging mechanisms and the notions of grid to vehicle and vehicle to grid architectures.

In Section 2, the types of electric vehicles and their operation are discussed in detail and in Section 3 a comparative assessment is presented. In Section 4, the current and future grid to vehicle charging methods and infrastructures are presented and in Section 5 the vehicle to grid technology is discussed as a potential future option for electric vehicles. The conclusions are summarized in Section 6.

2. Types of electric vehicles

Currently there are three main types of electric vehicles that have passed from the demonstration to the production stage of the manufacturing process [3]. These are shown in Table 1 and they are the hybrid electric vehicles (HEVs), the plug-in electric vehicles (PHEVs) and the full electric vehicles (FEVs). The major difference between these types of vehicles is that for the last two types, the battery can be externally recharged.

2.1. Hybrid electric vehicles

A HEV is a type of hybrid vehicle, which combines two distinct power sources in order to provide driving power. The two power sources are a conventional internal combustion engine (ICE) and a battery/electric motor system as shown in Fig. 1. The presence of the battery and the electric motor system is intended to achieve either better vehicle fuel economy or better performance than a conventional ICE vehicle. This is essentially achieved since the low efficiency ICE is now used in combination with a much higher efficiency power source, such as the battery. Currently, a variety of HEV types exist in the automotive market with varying degrees of independent ICE/electric motor operation. The size of the components, such as that of ICE and of the electric motor, can significantly influence the control strategy of HEV. The ratio between the maximum power of the electric motor and the maximum power of the power train is referred to as hybridization ratio. A high hybridization ratio results in a large electric path (electric motor and battery) and a small ICE. On the other hand, a low hybridization ratio results in a small electric path and a large ICE [4]. A simplified version of hybrid power trains is the so-called mild hybrid, which has an integrated starter generator (ISG) instead of an electric propulsion motor.

Typically, HEVs are equipped with a standard ICE and a battery pack connected to an electrical motor [5]. Full HEVs are able to perform in both the conventional vehicle transmission mode by utilizing the ICE with conventional fuel, typically gasoline, and/or in an electric power mode by using electrical power from the

Table 1
Types of electric vehicles.

Vehicle type	Internal combustion engine	Battery charging
Hybrid electric vehicle	Yes	On-board (internal)
Plug-in electric vehicle	Yes	On-board (internal) and/or external charging
Full electric vehicle	No	External charging

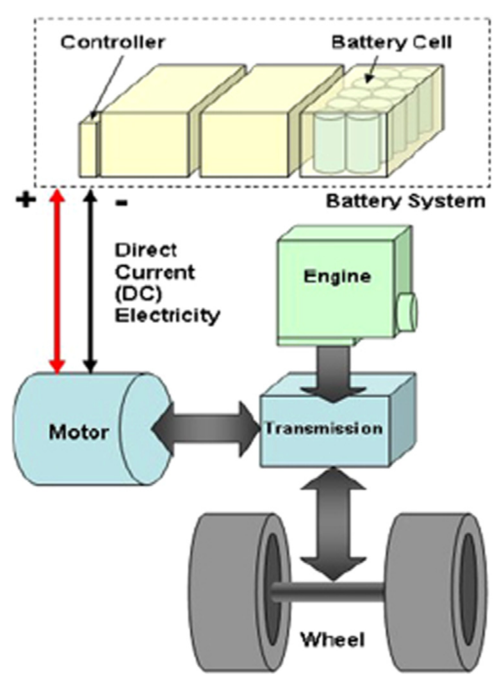

Fig. 1. Process diagram of a typical hybrid electric vehicle (HEV) [85].

battery to drive the electric motor as shown in Fig. 1. An essential feature of a HEV is the electric motor/generator system which (a) when used as a generator generates electrical power to charge the battery and start the vehicle's ICE when required and (b) when used as a motor, drives the vehicle by turning the vehicle's wheels [6]. Generally, conventional HEVs are charge-sustaining, i.e., while driving they maintain their batteries at a roughly constant state-of-charge and recharging occurs only from on-board electricity generation by the ICE coupled to the motor/generator or from the recapture of kinetic energy through regenerative braking.

2.1.1. Mode of operation

In a typical electric mode operation, the electric motor/generator uses power from the battery pack and acts as a motor to drive the vehicle at startup and at low vehicle speeds and acceleration where it offers high torque as shown in Fig. 2 [7]. The ICE, which can provide low torque at low vehicle speeds, is only engaged when higher speeds, faster acceleration or more power for charging the batteries is required and it is automatically started by the motor/generator acting as a starter [8]. This combined mode of vehicle operation allows the ICE to be utilized only at high efficiencies and to be normally switched off at traffic stops where it is anyway extremely inefficient. In the cases where the ICE is switched off, any accessory power requirements, e.g., air conditioning is provided by the battery pack. This limitation of ICE use results, therefore, in vehicle performance optimization and improved efficiency and lower emissions when compared to conventional gasoline vehicles [9,10].

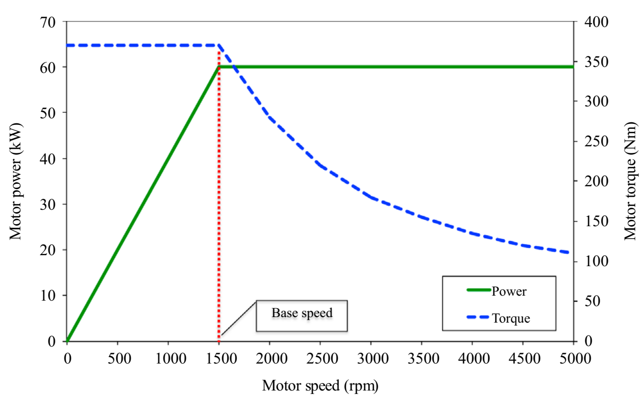

Fig. 2. Performance characteristics of a typical electric motor for traction.

2.1.2. Battery considerations

The HEV battery can be charged with the use of the motor/generator system, acting as a generator, both while driving and also while the car is stationary. In both cases, the vehicle's intelligence unit will be running the ICE in order to turn the generator system from where electrical charging power can then be extracted to the battery. Finally, the battery can also be charged via the regenerative braking technology. In this technology, the braking energy during the car's deceleration is used to charge the battery [11]. During deceleration, the regenerative brakes put the vehicle's electric motor into reverse mode and by running backwards the car's wheels are slowing down. While running backwards, the motor also is acting as a generator producing electricity that is used to charge the car's batteries. Regenerative brakes are more effective at lower speeds and in stop-and-go driving situations, i.e., in city traffic. Hybrid cars also employ friction brakes, as a back-up system in case where regenerative braking power is not enough to fully stop the car [12].

HEVs typically use a nickel cadmium (NiMH) battery pack which is typically allowed to be charged up to 40–60% of its maximum capacity to prolong battery life as well as to provide a reserve capacity in case of charging through regenerative braking [13]. A typical battery pack output voltage is 273.6 V with a 6.5 A h capacity and a weight of 53.3 kg. The total hybrid travelling range per gasoline fill-up is 900–1200 km. Essentially, the vehicle's electric travelling range, which is the distance the vehicle can travel only running on battery, is determined by the battery energy potential, while the acceleration rate and the maximum vehicle speed that can be reached in electric mode is determined by the battery power potential [5]. However, because of the continuous availability of the ICE as a back-up power source, and because of the fact that HEVs are run on charge sustaining mode without actually depleting their batteries, electric range and maximum vehicle speed are not as critical parameters to be considered in a hybrid vehicle battery design compared to PHEVs and, more importantly, FEVs.

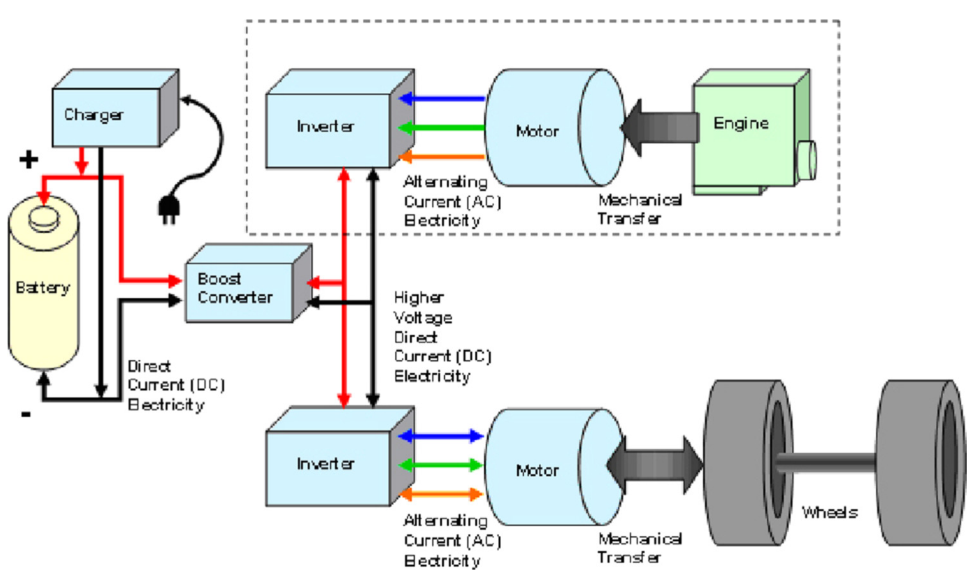

Fig. 3. Process diagram of a typical series plug-in hybrid vehicle (PHEV) [86].

2.2. Plug-in hybrid electric vehicles

PHEVs are a new and upcoming technology in the transport sector. Basically, they are similar to HEVs in that they have both an ICE and a battery pack as a means to provide driving power. In fact, PHEVs are defined as HEVs that have a battery storage system of 4 kW h or more, a means of recharging the battery from an external source and the ability to drive at least 16 km in electric mode [14]. These vehicles are able to run on fossil fuels and on electricity or a combination of both, leading to a wide variety of potential advantages including reduced dependence on oil, increased fuel economy, increased power efficiency, lower greenhouse gas emissions and vehicle-to-grid (V2G) technology [15]. In terms of efficiency, PHEVs have the potential to be even more efficient than HEVs since a more limited and selective use of the ICE would increase total combined vehicle efficiency and allow the ICE to be used even closer to its peak efficiency by operating only at high vehicle speeds [7].

Gasoline is the typical fossil fuel used in PHEVs operation but diesel or, to a lesser extent, ethanol can also be used. PHEVs do not utilize the ICE to charge the battery to the same extend as in HEVs, where this is the primary mode of charging. Instead, these types of vehicles have a battery pack that can be fully charged by the electricity grid by plugging the vehicle into a standard electrical outlet of 120/240 V AC. In addition, regenerative braking is also a feature of PHEVs which can also provide an on board battery charging alternative. Several studies have found that when charged from the electricity grid, PHEVs may emit less CO_2 and other pollutants over their entire fuel cycle than conventional ICE vehicles and HEVs [16]. Thus PHEVs may reduce the emissions impact of the transport sector in many regions provided that the grid electricity is effectively a cleaner source of transportation fuel than gasoline or diesel fuels [17]. This means that the fuel mix used in electricity generation has to produce fewer emissions than the average emissions of a conventional gasoline car. As a comparison to a HEV, a PHEV may offer 25–55% reduction in NO*x*, 35–65% reduction in greenhouse gases and 40–80% reduction in gasoline consumption [7]. Specifically with regard to greenhouse gas emissions, one of the great advantages of PHEVs or, for that matter, the FEVs is that the electricity used to power the vehicle may come from any combination of energy sources including zero emission renewable energy sources such as hydropower, solar, or wind. In such a case, PHEVs greenhouse gas emissions would be close to zero [18,19]. Therefore, in order to reap the full environmental benefits of PHEVs, their market uptake should be ideally combined with the penetration of zero emission electricity generation technologies.

2.2.1. Modes of operation

There are currently three main designs of PHEVs. These are the series, the parallel and the series/parallel designs. In the series design, shown in Fig. 3, the vehicle's wheels are only rotated by the electric motor and not the ICE. The ICE is only used to turn a generator which in turn supplies electrical power to the electric motor system which provides driving power [7]. The battery can store any excess charge produced by the engine. In the parallel design, which is very similar to a HEV design, both the engine and the electric motor can drive the vehicle's wheels independently or even simultaneously through mechanical coupling. Finally in the series/parallel hybrid design the vehicle has the flexibility to operate in either series or parallel mode.

Regardless of the design, PHEVs may offer two basic modes of operation. These are the charge-depleting mode and the charge-sustaining mode. Variations or combinations of these two modes that may be additionally available in some PHEVs are termed blended mode and mixed mode. These modes manage the vehicle's battery discharge strategy and their use has a direct effect on the size and type of battery required. The charge depleting mode, also used in FEVs, allows a fully charged PHEV to operate exclusively on electric power until its battery state of charge is depleted to a predetermined level, at which time the vehicle's ICE will be engaged [20]. A slight variation of the charge-depleting mode is the blended mode of operation, where the ICE is engaged prior to the battery depletion level being reached [21]. The blended mode is employed by PHEVs which do not have enough electric power to sustain high speeds, or speeds above a certain value, without the help of the ICE [22]. A blended operation mode can typically increase the distance travelled by a fully charged PHEV compared to charge-depleting mode alone [23]. The charge-sustaining mode is identical to the mode used by HEVs and combines the operation of the vehicle's two power sources in such a manner that the vehicle is operating as efficiently as possible without allowing the battery state of charge to move outside a predetermined narrow band. If the mixed mode of operation is available, then once a PHEV has exhausted its electric range in charge-depleting mode, it can switch automatically into charge-sustaining mode.

As an example, [24], a PHEV with an electric range of 32 km may begin a trip with 8 km of low speed in charge-depleting mode, then get onto a freeway and operate in blended mode for 32 km, using 16 km worth of electric range with the corresponding economy in fuel. Then, the driver might exit the freeway and drive for another 8 km without the ICE until the full 32 km of electric range are exhausted [24]. At this point, the vehicle can revert back to a charge-sustaining mode for another 16 km until the final destination is reached. Such a mixed mode trip contrasts to a charge-depleting mode trip, which would be driven first within the limits of a PHEV's battery.

2.2.2. Battery considerations

Since batteries are DC devices, while grid power is AC, on-board DC chargers are mounted inside the PHEV. The charger's power capacity is only limited by practical vehicle considerations such as space and weight. In practice, this means that PHEVs generally do not carry high power chargers in order to avoid excess weight [25]. Off-board chargers are, therefore, also available which can be as large as needed and mounted at predetermined locations, such as, the garage or dedicated charging stations [26]. These chargers can handle much more charging power and therefore charge the batteries in less time. However, the output from these chargers is usually DC, thus needs to be regulated to suit the particular vehicle battery voltage requirements. Modern charging stations have a system for identifying the voltage of the battery pack and adjusting the output of the charger accordingly [27].

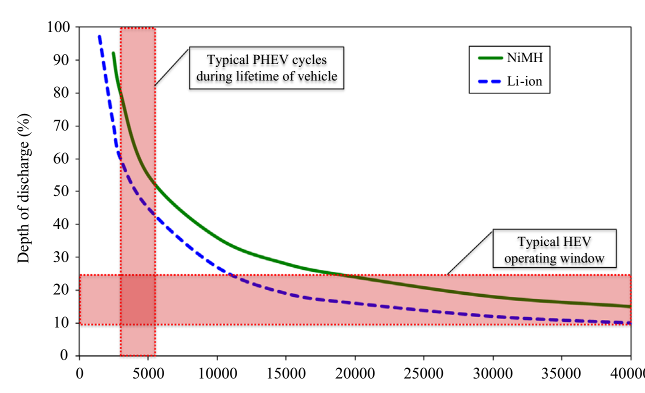

Fig. 4. Cycle life characteristics of Li-ion and NiMH energy storage technologies.

PHEVs operating with charge-depleting mode of operation necessitate deeper battery charging, up to 95%, and discharging, up to 80%, cycles compared to HEVs as highlighted in Fig. 4. The typical HEV operating window, which is around 10–20% depth of discharge, affords the battery a very large number of lifecycles, in contrast to a PHEV [28]. In addition, PHEVs require larger battery energy potential to allow for extended electric travelling ranges. PHEVs, therefore, require durable and larger battery types, able to withstand deep discharges while at the same time offering the highest possible number of full cycles and battery life [29]. Therefore, design issues and trade-offs between battery life, capacity, energy, power, weight and, most importantly, cost need to be solved for this type of vehicles. In fact, one of the disadvantages of PHEVs compared to HEVs is the unavoidable increased cost of the battery pack since this has to necessarily be larger in size and heavier [30]. Essentially, the optimum battery size for a PHEV depends whether the aim is to reduce gasoline consumption, battery maintenance costs or vehicle emissions [31]. Also, battery size would critically depend on the distance that the vehicle will be expected to be driven between successive battery charges [7].

Overall, two types of batteries would be suitable for use in PHEVs. These are the nickel cadmium (NiMH) and the lithium-ion (Li-ion) batteries. NiMH offer inferior energy and power densities than Li-ion batteries, translated to lower electric travelling range and lower maximum vehicle speed and acceleration performance. Instead NiMH batteries can be more durable and can sustain higher number of lifetime cycles for deep discharging up to 80%, than Li-ion [32]. This is clearly shown in Fig. 4, where a NiMH battery is shown to achieve 4000 cycles when discharged to 80% depth of discharge while to achieve the same number of cycles, a Li-ion battery can only be discharged to approximately 50% depth of discharge. This can effectively mean that NiMH batteries have a better chance of extending their life to last the lifetime of the PHEV, estimated to require at least 4000 cycles [33]. Despite this, however, the current technology for PHEVs is based on the Li-ion battery. The reason is that advanced Li-ion battery technology is under significant development and can offer extended energy densities by both mass and volume, and battery life expectancy [34]. This is translated to higher electric travelling ranges and maximum top speeds. A typical electric travelling range achievable is approximately 20–60 km with a maximum speed of 160 km/h [35]. The electric travelling range is supplemented by an additional gasoline-only range to reach a total travelling range of 600–900 km. Naturally, the electric travelling range potential of a specific PHEV determines the charging power consumption of the vehicle. It is generally reported that the typical power consumption of PHEVs is around 0.125 kW h/km. More specifically, it has been estimated that 8 kW h are required to fully charge a PHEV after a 64 km trip.

2.3. Full electric vehicles

FEVs are powered only by an electric motor or a traction motor rather than a gasoline ICE. Vehicles powered by fuel cells are also considered to be electric vehicles. Electricity is typically generated by on-board rechargeable battery packs and in some cases through the use of capacitors or flywheels. The charging of the battery can be made in way similar to those of PHEVs, i.e., either in standard home electricity outlets or in external dedicated charging stations.

As is the case with HEVs and PHEVs, FEVs have the potential to provide a significant decrease of harmful greenhouse gases emissions of the transport sector compared to conventional ICE vehicles. In fact, the level of emission reductions from FEVs is potentially much higher than that of PHEVs [36]. This of course is critically dependent on the efficiency and on the emissions intensity of the electricity generation system in the specific region where the vehicle will be recharging its battery pack. Aside from the potential emissions advantage, FEVs also exhibit certain advantages in performance compared to conventional gasoline vehicles [37]. These advantages are the result of their built-in high power battery packs. Such battery packs drive electric motors with inherently higher torque in lower vehicle speeds than ICE meaning that FEVs can be much quicker and accelerate from rest faster than conventional vehicles without using any transmission or clutch systems. However, a disadvantage of FEVs that is sometimes overlooked is that the absence of an ICE minimizes the available heating capability of the vehicle's internal heating system. This could prove to be a significant factor in colder climates that needs to be addressed.

Today a number of FEVs are available in the automotive market. The most recently manufactured FEVs use state-of-the-art Li-ion battery packs and have therefore improved performance compared to NiMH vehicles or older technology Li-ion batteries. A typical FEV has a range of approximately 120–390 km, and a top speed of 200 km/h.

2.3.1. Mode of operation

The basic systems of a FEV include the electric motor, the battery pack and the electric motor controller as shown in Fig. 5. Under normal operation, the motor controller is powered by the battery pack and delivers regulated and controlled power to the electric motor in order to turn the vehicle's wheels [38]. The amount of power, or voltage, to be delivered to the motor by the controller is determined by the position of the accelerator pedal which is connected to a pair of variable resistors. At any given instance, the relative resistance of these resistors provides the signal to the controller of how much electric power should be

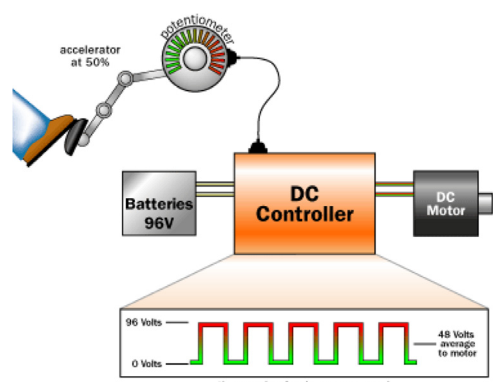

Fig. 5. Process diagram of a typical full electric vehicle (FEV) [87].

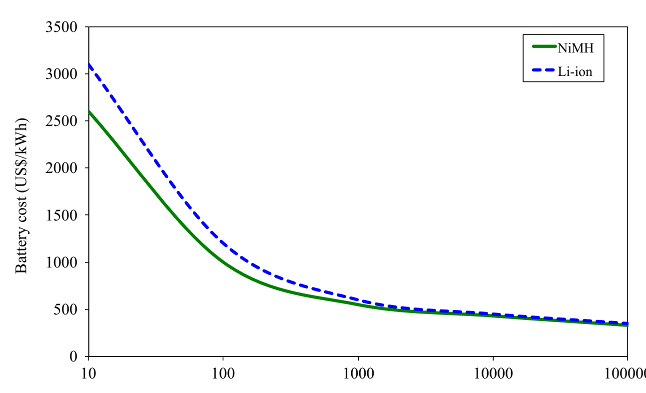

Fig. 6. Decline in battery costs based on production volume.

delivered to the electric motor [39]. The controller can deliver zero power, or zero voltage, when the car is stopped and the accelerator is not pressed at all, full power, or full battery voltage, when the driver fully presses the pedal, or any intermediate power level in between [40,22]. For example, when the accelerator is pressed at 50% the controller chops the full battery voltage at a very high frequency to create an average voltage delivered to the motor equal to half the full battery voltage [41]. The chopping/pulsing is achieved via a system of on/off switches built in the motor controller system. In the case of the 50% pressed accelerator pedal, full voltage power would be switched "on" 50% of the time and switched "off" the remaining 50% of the time. Most controllers operate at a frequency of 15 kHz since at such high frequencies the controller pulsing is not audible to human ears Fig. 6.

A FEV could be using either a DC or an AC electric motor. A DC motor would typically be in the 20–30 kW range and require full battery voltage of up to 200 V. Such a motor is coupled to a DC controller which could be in the 40–60 kW range. An AC motor uses a three-phase motor running at 240 V AC with a 300 V battery voltage and typically has higher rated power. An AC motor/controller system is more complicated than the respective DC system due to the fact that the voltage received by the controller from the batteries is DC. Essentially the AC controller uses six sets of power transistors to convert the 300 V DC into 3-phase 240 V AC.

2.3.2. *Battery considerations*

In contrast to PHEVs, FEVs need to operate their battery across the whole range of vehicle speeds since no ICE exists. In addition, in order to minimize FEV driver insecurity concerning limited electric travelling range, the battery energy potential needs to be high enough to guarantee at least a minimum driving range that would be sufficient to cover a daily routine driving [42]. These factors provide the need for high-power, high-energy battery packs which would be able to withstand high discharging and high charging levels and also be reasonably light [43]. However, an increased battery energy density would also increase charging times considerably. Such features are only available through either NiMH or Li-ion batteries, which however come at a much higher cost. The cost of batteries is the most significant parameter contributing to the high cost of FEVs today and represents the most important obstacle to the full commercialization of FEVs.

The short driving range and the cost of battery system explain the increased focus on fuel cell technology as a competitive alternative today for FEVs [44]. Compared to batteries, fuel cells can be smaller, lighter and instantly rechargeable. Fuel cell vehicles can be powered by chemical reactions in a fuel cell that create electricity to drive very efficient electrical motors. Finally, fuel cells are using hydrogen, have none of the environmental problems associated with electric power consumption [45]. Potentially, the atmospheric pollution could be, therefore, minimal provided that hydrogen is produced by electrolysis using electricity from zero emission energy sources [46].

In addition to the main battery pack, most FEVs have another battery on board. This is the standard 12 V lead-acid battery that every conventional car has. The 12 V battery provides power for accessories, such as, radios, air bags, headlights, wipers, power windows, fans and instruments. Since all of these devices are readily available and standardized at 12 V, it is easier from an economic standpoint for an electric car to use them and, therefore, a FEV has a standard 12 V lead-acid battery to power all the accessories [47]. To keep this auxiliary battery charged, a FEV also has a converter from DC to DC. This converter takes in the DC power from the main battery e.g., at 300 V, and converts it down to 12 V to recharge the accessory battery. When the car is on, the accessories are powered from the DC-to-DC converter, but when the car is off, are powered from the 12 V battery as in any gasoline-powered vehicle.

3. Comparative assessment

A comparison of the technical characteristics of the three types of electric vehicles is shown in Table 2. FEVs operate only on battery charge and therefore always employ the charge depleting mode of operation requiring high power, high energy battery packs primarily offered by Li-ion batteries [48]. On the other hand, PHEVs offer the possibility of on-board battery charging and the option of charge depleting or charge sustaining modes of operation [49]. Therefore, their demands on battery performance are less strict compared to FEVs and can be satisfied by both Li-ion and NiMH batteries. Finally HEVs, which were the first type of electric vehicles to be manufactured, offer higher travelling range compared to PHEVs and FEVs due to the existence of the ICE [50].

Essentially, there are two efficiency indicators that are useful to evaluate the fuel economy and the tailpipe emissions of electric vehicles. The first is the tank-to-wheel efficiency and the second is the well-to-wheel efficiency. The tank-to-wheel efficiency refers to the operating efficiency of the car itself and provides the car's actual fuel economy. The well-to-wheel efficiency is a more comprehensive efficiency indicator since it includes, apart from

Table 2
Comparison of technical characteristics of electric vehicles.

Vehicle type	Mode of operation	Battery type	Maximum driving range (km)	Top speed (km/h)
Hybrid electric vehicle	Charge-sustaining	NiMH	900–1200 (hybrid)	170
Plug-in electric vehicle	Charge-sustaining	NiMH	20–60 (electric)	160
	Charge-depleting Mixed mode	Li-ion	900 (hybrid)	
Full electric vehicle	Charge-depleting	Li-ion	120–390	80–200

Table 3
Comparison of fuel economy and CO_2 emissions of electric vehicles.

Vehicle type	Electricity consumption (kW h/km)	Tank-to-wheel fuel economy (l/100 km)	Well-to-wheel fuel economy (l/100 km)	CO_2 emissions (gCO_2/km)[a]
Hybrid electric vehicle	N/A	4.7	4.7	109
Plug-in electric vehicle	0.225	3.92	5.68	132
Full electric vehicle	0.175	1.96	3.77	88

[a] Based on the well-to-wheel efficiency of the vehicle.

the tank-to-wheel efficiency, the efficiency of the fuel/electricity production infrastructure from the oil-well to the tank [28].

As an example, a comparison of the tank-to-wheel and the well-to-wheel efficiencies of a conventional gasoline vehicle and a FEV will be described. Typical tank-to-wheel efficiency of any gasoline vehicle is primarily limited by the ICE peak efficiency, which is theoretically around 38%. In reality however, conventional gasoline vehicle efficiencies would be much less, even approaching 15–20%, depending on the mode of driving of the vehicle [51]. Tank-to-wheel efficiency of a FEV is limited primarily by the energy cycle, charging and discharging, of the battery. FEVs using Li-ion batteries can reach efficiencies of at least of 75%, while with lead-acid batteries efficiency can drop to 60%. This is of course still significantly higher when compared to the efficiency of ICE based conventional gasoline vehicles [52]. Essentially, the efficiency gains in FEVs are achieved due to the better performance of the electric motor instead of the ICE at lower speeds and due to the fact that FEVs do not consume energy when not moving, unlike ICE which continue running even during idling. However, when considering the well-to-wheel efficiency of these two types of vehicles, the situation is different. In this case, the difference in efficiency is significantly reduced. The reason is that the generation of electricity necessary for FEVs battery charging, relies on fossil fuels through the use of power generators operating at efficiencies between 30 and 60% [53]. The final difference in efficiency between a conventional ICE vehicle and a FEV would then depend on the fuel mix and type of generators used in the electricity generation system of the specific region or country where the FEV will be charging its battery. A detailed analysis of the advantages and disadvantages of electric vehicles versus conventional ICE vehicles is provided in [54].

Generally, the tank-to-wheel efficiency is used to provide a fuel economy comparison for vehicles of the same category type. It is also used for the same purpose to compare vehicles across different vehicle category types i.e., for conventional gasoline vehicles, FEVs, or PHEVs. The well-to-wheel efficiency is however necessary in order to provide a meaningful comparison of vehicle tailpipe emissions across these different types of vehicle categories. Typical values for tank-to-wheel and well-to-wheel fuel economies are tabulated in Table 3 [55–58]. The potential benefits of PHEVs in terms of reducing CO_2 emissions are provided in [59] for different types of PHEV vehicles.

4. Grid to vehicle charging

Grid to vehicle charging (G2V) refers to the process of battery charging of the electric vehicles from the electricity grid infrastructure [2]. Clearly, electric vehicles such as PHEVs and FEVs need to charge their battery packs through the electricity grid in order to be able to move. Battery charging is mostly achieved through the use of conventional household outlets. However, high charging times and the need for vehicle charging in outside locations for more frequent and quicker charging has resulted in the advent of publicly available charging stations [60]. These stations can be independent or belonging to a network of stations and may offer state-of-the-art smart grid applications [31].

4.1. Household outlets

Recharging the battery from a regular household charging system has the advantage of convenience, however the disadvantage is increased charging time and the possible absence of electrical outlets at convenient locations for charging such as the garage. A typical USA and Japanese household has a 120 V outlet with a 15 A circuit breaker, although the maximum current to be drawn by the vehicle in practice may be limited to less than 15 A. Typically the power output from such outlets is between 1.4 and 1.5 kW h. Therefore, for a typical FEV, a 12 to 15 kW h full battery recharge would take 10 to 12 h. For European household outlets the typical respective ratings are 220/240 V at 30 A supply. However, the maximum power that can be eventually drawn by the vehicle will limited by the maximum power rating of its on-board battery charger [61]. Despite this, a 220 V outlet would allow significantly faster charging than the 110 V and for FEVs with a 3.3 kW h on-board battery charger, such as the Leaf, it could fully recharge a 12 to 15 kW h battery pack in 4 to 5 h.

In order to reduce full battery charging time, some FEVs that possess high energy density batteries, have the option of proprietary, custom-made charging units which allow faster charging. These are DC fast charging units with a voltage of 480 V DC and 125 A charging current, or a 500 V DC unit. Other designs for faster charging include wall-mounted AC charging units allowing higher current circuit breaker ratings e.g., 240 V 70 A. One of the disadvantages of frequent fast-charging appears to be that the gradual battery capacity loss can be as much as 10% higher in a 10 year period than in the case of normal charging with the 220 V home outlet [62].

4.2. Electric vehicle network

The electric vehicle network is a proposed infrastructure system of publicly-accessible charging stations and possible battery swap/switch stations to charge electric vehicles. Government, car manufacturers, electricity utility companies, and charging infrastructure providers have entered into many agreements to create such networks. Already a number of charging stations are planned or in place in countries such as Australia, China, Denmark, Norway, France, Italy, Estonia, Germany, Switzerland, Ireland, Netherlands, Poland, UK, Spain, Israel and the USA. In Germany and France, which together with the UK are currently the leading European countries in terms of number of charging stations, the major electricity utility companies have entered into partnerships with electric car manufacturers to develop further the infrastructure of charging stations [63]. As an example is the RWE AG-Daimler AG partnership which has already set up of 60 charging stations in Berlin servicing the needs of over 100 e-Smart FEVs. Other similar alliances include EDF-Toyota, EDF-Renault/Nissan and Vattenfall-BMW.

The charging networks that are already in place today offer conventional AC charging outlets, based on the prevailing national vehicle charging specifications, standards and protocols. During conventional AC charging, energy is transferred to the vehicle's on-board charger. In the USA, the AC charging standard used is the SAE J1772 standard, which is the same standard used in electrical outlets in homes in the USA and Japan, and is either 120 V 16 A, called Level 1, or 220 V 32 A, called Level 2 outlets. In Europe, the AC charging standard used is the IEC62196, Mode 1 which is a 230 V 16 A outlet. In Australia, the standard used is the AS 3112 with 230 V 15 A outlets. Finally, in the UK, charging stations use the BS 1363 standard 230 V 13 A outlets. The charging outlet standards are summarized in Table 4.

In contrast to conventional AC charging, the option of fast charging is offered only in a few countries. Fast charging can be either AC or DC depending on the specific country or region and the specification it adopts. In any case, fast charging is usually denoted as Level 3 charging in the USA and as Mode 3 (AC fast charging) or Mode 4 (DC fast charging) in Europe. During fast charging, the energy is typically transferred to off-board charger and requires devoted connectors [42]. These connectors usually provide additional features during the charging process, such as inability of the vehicle from moving during charging, or option for

Table 4
Electric vehicle charging outlets.

Region	Conventional charging standard	Conventional charging conditions	Fast charging conditions
USA	SAE J1772	Level 1: 120V, 16A Level 2: 220V, 32A	Not yet decided Level 3 AC or DC
Europe	IEC 62196	Mode 1: 230V, 16A	Mode 3: AC 400V, 32A
Australia	AS 3112	230V, 15A	SAE J1772
UK	BS 1363	230V, 13A	CEE blue: 230V, 32A

integration of the vehicle being charged into smart-grid scenarios [64]. Taking this idea further, the electric vehicle recharging network can have an intelligence built into it, through tailored software, allowing drivers to find out where their nearest charging point is, to evaluate how much they need to recharge given the current state of their battery, and when would be the most cost-effective time for them to recharge given current prices offered by the electricity grid [65].

In Europe, fast charging is usually AC through Mode 3 standard which is 400 V 32 A (in the UK CEE blue is also used with 230 V 32 A) and Type 2 connector. Ireland applies a DC fast charging using the Charge de Move (CHAdeMO) protocol with voltages from 300 to 500 V DC 125 A. However, in the absence of a universal connector/outlet standard or specification, most fast charging outlets tend to vary from country to country and be custom made to suit the specific vehicle model of the manufacturer participating in the specific network [66].

Another alternative to achieve rapid recharging of completely discharged battery packs is the battery replacement or battery swapping option [67]. In this way, instead of recharging the battery it could be mechanically replaced on special stations in just a few minutes. This alternative could apply to batteries with very high energy densities that require significant time to recharge. In the future, batteries with the greatest energy densities, such as metal-air fuel cells, which cannot be recharged in a purely electric way appear to be promising candidates for battery swaps.

Taking into consideration the current ranges of electric cars, it is clear that until a charging infrastructure (even one that consists of simple 240 V electrical outlets in convenient places) is developed, electrical vehicles will remain best suited for local driving in short ranges around the home. In order to facilitate the penetration of electric vehicles as a competitive alternative to conventional vehicles, mass provision of charging points and networks must precede consumer availability of electric vehicles. The geographic location of the charging points would play a critical role in the adoption of electric vehicles in each area, especially FEVs, and would have to take into consideration the concentration of both residential and office areas [68].

4.3. *Benefits and problems associated with G2V charging*

PHEVs and FEVs may allow for more efficient use of the existing electricity generation capacity which during off-peak hours is mostly sitting idle as operating reserve. This can be achieved by the charging of the vehicle's battery primarily during off-peak periods, i.e., during the night. In such a case, the charging of PHEVs or FEVs would increase electrical demand during the night but this would allow the utilities to better balance their electricity production loads, leading to improved operating efficiencies. In addition, the increase of the off-peak demand would narrow the gap between peak and off-peak demand, thus allowing optimum use of generating units [69]. The major problems for the electricity network, identified through various studies, during electric vehicle charging can be summarized as increased transformer loading, thermal loading of conductors, unbalance of network, reductions in voltage levels, power losses and harmonic distortion [69].

The most potential problem of electric vehicle charging is that of exceeding grid power capacity and grid infrastructure capability. In theory, if all or a large proportion of private vehicles were to charge their batteries at the same time, i.e., at night, this would increase substantially the energy consumption and electricity demand. In some cases, the increase of demand would be higher than the available local transformer power supply causing transformer overload or the current carrying capability of the transmission or distribution grid infrastructure causing severe thermal loading of conductors. For example, it has recently been reported by UK's National Grid that the high voltage transmission system can manage the demand of about 1 million electric cars, however penetration up and above that becomes a real issue [70]. In addition local distribution networks in cities like London may struggle to balance their grids if drivers chose to plug-in their vehicles at the same time.

In terms of transformer overload and/or thermal loading of grid conductors, the situation is aggravated when vehicle charging takes place during peak periods and when the battery is fast charged with higher charging currents rather than being charged through conventional charging outlets. Studies have found that advanced and smart metering techniques, such as the advanced metering infrastructure (AMI) can cause mitigation and better control of overloads on the distribution network. Such techniques include stagger charge, whereby charging of batteries across a number of different household outlets is staggered and controlled in such a way as to allow load balancing and avoidance of overloads, and household load control. Household load control allows consumers the choice to shed some non-essential loads in order to recharge their electric car more quickly.

In case vehicle charging is left unregulated, consumers will continue to charge their vehicles randomly and irrationally [71]. Although random charging may decrease the possibilities of transformer overloads it may cause distribution network imbalance especially since charging is done through single phase electric outlets. Load flow analysis and studies on the Belgian distribution grid have shown that impacts of load imbalance are increased voltage drops and power losses. The conclusion of the studies was that the integration of electric vehicles deeply affects the power losses and voltage deviations in the distribution grid and that these changes are far too important to be ignored. Rather they need to be quantified in order to preserve the reliability of the grid. In addition, it has been identified that coordinated or "smart" charging of electric vehicles is far preferred than uncoordinated charging in terms of reducing power loss and voltage drop [72]. Therefore, electric vehicle charging must be coordinated via operators and other multi-agent systems in order to maintain the integrity of the distribution grid. The advent of intelligent charging stations that can communicate with the grid can play a vital role. Also, increased power harmonics from PHEVs power electronics can pose an additional impact on distribution grid transformers. The impacts of harmonics would be widely varied in different parts of the power grid. Hence future distribution network planning, typically performed in long term planning using local load forecasts, needs to assess potential private transport

scenarios and possible electric vehicle fleet power demands, and reinforce the local grids accordingly.

5. Vehicle to grid electricity

Vehicle to grid (V2G) electricity refers to the technology of bidirectional flow of electricity between the electric vehicle and the grid. V2G enabled vehicles can therefore transfer electricity both to and from the power grid as necessary [65,73]. If this technology is in place, electric vehicles could use their excess battery capacity to export power back to the grid, and can potentially assist and supplement electricity supply during peak hours [74,75]. This would be beneficial to the electric utility, as it would allow for lower electricity generation costs since the more expensive peaking units would be committed to a lesser extent [76]. If this export of electrical power is combined with off-peak import (charging) it would potentially even out the demand for electricity which would be financially beneficial to both the electric utilities and the electric vehicle owners. For the utilities a smoother demand curve would translate to more economic unit commitment and economic dispatch [77]. The vehicle owner would stand to gain from the difference of buying electricity (charging) at the low off-peak rates, while selling it to the grid at higher peak demand rates. In addition, the exported electrical power can be used also for the optimization of reactive power requirements to the distribution network and improve grid stability. In this scenario, the electric vehicle performs in a manner very similar to distributed generation as it supplies power when power is needed and consumes power when there is an excess. In fact, electric vehicles could be used to stabilize the grid from any intermittent energy sources with generation profiles that do not match demand profiles, such as wind power [78,79].

Such an export of electrical energy from electric vehicles could take place either in the G2V charging stations themselves or in private home outlets [80]. The intelligent connection of the charging station to the grid can allow vehicle owners to communicate with the grid operator and inquire when would be optimal times not just for "downloading current" from the grid (charging or recharging batteries) but also for "uploading current" to the grid (discharging batteries) when convenient to do so [81]. The electrical energy has to be exported to the grid via permission of the grid operator who would have to ensure the balance of load across the network. In cases of energy exported from vehicles using the single-phase home outlets, the issue of maintaining the three-phase balance of load in the distribution network would become more complicated.

V2G technology needs to offer the possibility to recharge the electric vehicle in order to ensure that the vehicle will be able to reach its next destination using electric energy [45,82]. Hence vehicles should be able to quit V2G services in order to recharge sufficiently before departure. Furthermore, widespread use of V2G services can lead to critical states of the distribution network, such as islanding.

Currently the base standards and regulation framework do exist to ensure the transition to a market including electric vehicles, whether PHEVs or FEVs [83]. However, if the market is to expand to include a significant share of electric vehicles, standards and regulation will need to be expanded in order to incorporate the entirety of the system impacts of the electric vehicles, from generation impacts to the V2G smart-grid to the end-user [84].

6. Conclusions

In this work, an overview regarding electric vehicle technologies and associated charging mechanisms is carried out. The review covered a broad range of topics related to electric vehicles, such as the basic types of these vehicles and their technical characteristics, fuel economy and CO_2 emissions, the electric vehicle charging mechanisms and the notions of grid to vehicle and vehicle to grid architectures.

In particular three main types of electric vehicles, namely, the hybrid electric vehicles (HEVs), the plug-in electric vehicles (PHEVs) and the full electric vehicles (FEVs) were discussed in detailed. The major difference between these types of vehicles is that for the last two types, the battery can be externally recharged. In addition, FEVs operate only on battery charge and therefore always employ the charge depleting mode of operation requiring high power, high energy battery packs. On the other hand, PHEVs offer the possibility of on-board battery charging and the option of charge depleting or charge sustaining modes of operation. Finally HEVs, which were the first type of electric vehicles to be manufactured, offer higher travelling range compared to PHEVs and FEVs due to the existence of the internal combustion engine.

Although tank-to-wheel efficiencies of electric vehicles show that they have higher fuel economies than conventional gasoline vehicles, the well-to-wheel efficiency is a more appropriate measure to use for comparing fuel economy and CO_2 emissions in order to account for the effect of electricity consumption from these vehicles. From the perspective of a full cycle analysis, the electricity available to recharge the batteries must be generated from renewable or clean sources in order for such vehicles to have zero emissions. On the other hand, when electric vehicles are recharged from electricity produced from conventional technology power plants such as oil or coal-fired plants, they may produce equal or sometimes more greenhouse gas emissions than conventional gasoline vehicles.

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